International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 3 Issue 6, June-2014, pp: (86-90), Impact Factor: 1.252, Available online at: www.erpublications.com

Specifications and recommendations for recycled materials used for various applications

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Abstract: A comparative analysis of the experimental results of the properties of fresh and hardened concrete with different replacement ratios of natural with recycled coarse aggregate is presented in the paper. Recycled aggregate was made by crushing the waste concrete of laboratory test cubes and precast concrete columns. Three types of concrete mixtures were tested: concrete made entirely with natural aggregate (NAC) as a control concrete and two types of concrete made with natural fine and recycled coarse. Ninety-nine specimens were made for the testing of the basic properties of hardened concrete. Load testing of reinforced concrete beams made of the investigated concrete types is also presented in the paper. Regardless of the replacement ratio, recycled aggregate concrete (RAC) had a satisfactory performance, which did not differ significantly from the performance of control concrete in this experimental research. However, for this to be fulfilled, it is necessary to use quality recycled concrete coarse aggregate and to follow the specific rules for design and production of this new concrete type.

Keywords: mechanical properties; load test; structural concrete, recycled aggregate; recycled aggregate concrete;

INTRODUCTION

The production of demolition and construction waste has been increasing at a gradual rate in recent years. The use of these materials as recycled unbound base course in new roadway construction has become more common in the last twenty years. Recycled roadway materials are typically generated and reused at the same construction site, providing increased savings in both money and time. It has been speculated that in some municipalities recycled materials costs less to use than conventional crushed-stone base material by as much as 30%. The most widely used recycled materials are recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA). RAP is produced by removing and reprocessing existing asphalt pavement and RCA is the product of the demolition of concrete structures such as buildings, roads and runways. The production of RAP and RCA results in an aggregate that can be well graded and of high quality. The aggregates in RAP are coated with asphalt cement that reduces the water absorption qualities of the material. In contrast, the aggregates in RCA are coated with a cementitious paste that increases the water absorption qualities of the material.

There is some ambiguity regarding the nomenclature involved in the production of RAP. The following classification is recommended to remove ambiguity in nomenclature: RAP refers to the removal and reuse of the hot mix asphalt (HMA) layer of an existing roadway; full depth reclamation (FDR) refers to the removal and reuse of the HMA and the entire base course layer; and recycled pavement material (RPM) refers to the removal and reuse of either the HMA and part of the base course layer or the HMA, the entire base course layer and part of the underlying subgrade implying a mixture of pavement layer materials. Unless specified, these three distinct recycled asphalt materials can be collectively referred to as RAP.

RAP is typically produced through milling operations, which involves the grinding and collection of the existing HMA, and FDR and RPM are typically excavated using fullsize reclaimers or portable asphalt recycling machines. RAP can be stockpiled, but ismost frequently reused immediately after processing at the site. Typical aggregate gradations of RAP are achieved through pulverization of the material, which is typically performed with a rubber tired grinder.The production of RCA involves crushing the concrete material to a gradation comparable to that of typical roadway base aggregate. Fresh RCA typically contains a 4 high amount of debris and reinforcing steel, and the RCA must be processed to remove this debris prior to placement. The remaining concrete material after debris removal is further crushed and screened to a predetermined gradation. RCA can be derived from concrete pavements or buildings (building derived concrete).

Production

There is some ambiguity regarding the nomenclature involved in the production of RAP. Based on the experience of the Geo Engineering Program at the University of Wisconsin-Madison, the following classification is recommended to remove ambiguity in nomenclature: RAP refers to the removal and reuse of the hot mix asphalt (HMA) layer of an existing roadway(7) ; full depth reclamation (FDR) refers to the removal and reuse of the HMA and the entire base course layer; and recycled pavement material (RPM) refers to the removal and reuse of either the HMA and part of the base course layer or the HMA, the entire base course layer and part of the underlying subgrade implying a 2mixture of pavement layer materials.(6) Unless specified, these three distinct recycled asphalt materials will be collectively referred to as RAP.

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Material Properties

The gradation of RAP can be compared to that of a crushed natural aggregate, although with a higher content of fines. The high fine content is the result of degradation of the material during milling and crushing operations. In RPM the inclusion of subgrade materials in the recycled material also contributes to a higher instance of fines. Finer gradations of RAP are produced through milling operations compared to crushing operations. Table 1 provides a breakdown of typical physical and mechanical properties of RAP.

RCA is processed exclusively through crushing operations, and is very angular in shape. Depending on the crushing methods, the particle size distribution of an RCA can have a wide variability, with a lower particle density and greater angularity than would normally be found in more traditional virgin base course aggregates. Residual mortar and cement paste are typically found on the surface of the RCA, as well as contaminants associated with construction and demolition debris. The presence of this mortar contributes to a rougher surface texture, lower specific gravity, and higher water absorption than typical aggregates. The self-cementing capabilities of RCA are an interesting secondary property. The crushed material exposes un-hydrated concrete that can react with water, potentially increasing the materials strength and durability when used as unbound base course for new roadway construction. It follows that service life could also be extended as a result of these properties. Although widely acknowledged, not much actual documentation has been published regarding this secondary hydration.(5)Although the cause of self-cementing properties has been studied, the actual effect of such parameters as age, grade, and mix-proportions of the RCA on the overall cementitious effect has yet to be determined. This effect is outside the scope of this literature review. Table 2 provides a breakdown of typical physical and mechanical properties of RCA.

Table 1: Typical Physical Properties of RAP

Physical Properties	
Unit Weight	1940 - 2300 kg/m^3 (120 - 140 pcf)
Moisture Content	Normal: Up to 5% Maximum: 7 - 8%
Asphalt Content	Normal: 4.5 – 6%
Asphalt Penetration	Normal: 10 – 80% at 25°C (77°F)
Absolute Viscosity or Recovered Asphalt Cement	Normal: 4000 – 25000 poises at 60°C (140°F)
Mechanical Properties	
Compacted Unit Weight	1600 – 2000 kg/m^3 (100 – 125 pcf)
California Bearing Ratio (CBR)	100% RAP: 20 – 25% 40% RAP and 60% Natural Aggregate: 150% or Higher

Compaction Characteristics

Maximum dry unit weight (MDU) varied within a narrow range of about 1 kN/m^3 and optimum moisture contents within 3 % for both RAP/RPM and RCA samples. The average MDU was about 19-20 kN/m^3 for both RAP/RPM and RCA samples. However, the average OMC was higher for RCA (about 10%) than RAP/RPM (about 7%) samples due to higher absorptive capacity of RCA samples. OMC can be estimated empirically as a function of uniformity coefficient and percent absorption and MDU as a function of optimum moisture content for both RCA and RAP/RPM samples as given in RMRC Project No. 46 report.

Resilient Modulus and Plastic Strains

Resilient modulus is the primary design property of pavement materials. Various studies as well as the tests conducted on these samples indicate that the resilient modulus of both RCA and RAP/RPM are equal or higher than that of natural aggregate. Typically, a representative modulus is computed for base course termed Summary Resilient Modulus (SRM) as suggested in NCHRP 1-28a, corresponding to a bulk stress of 208 kPa. For the RAP/RPM samples, SRM ranged from 627 to 989 MPa. RCA samples had slightly lower SRM (ranging from 549 to 715 MPa) in comparison to RAP/RPM, while Class 5 natural aggregate has the lowest SRM (525 MPa). The resilient modulus of both RCA and RAP/RPM can be estimated empirically in terms of compositional characteristics such as grain size, asphalt content, absorption, percent fines as given in Project No. 46 report.Various studies indicate that the plastic strains of RAP is greater (nearly 10 times) than that experienced by natural aggregate and RCA. This may be of concern for potential conribution to rutting. This concern will be addressed in the design section.

Design

Determining the appropriate thickness of the pavement layers based on engineering properties is a critical task in the design of pavements, and can be particularly challenging when alternative materials such as recycled aggregates e.g., RAP, RPM, RCA or reclaimed road surface gravel (RSG) are used. A methodology to incorporate granular recycled aggregates as base course (alone and stabilized with binders such as fly ash, cement, cement kiln dust) in pavement design is developed. Mechanical behavior of these materials was characterized through a large-scale model experiment (LSME) as well as laboratory bench-scale resilient modulus (BSRM) tests in accordance with NCHRP 1-28a at the University of Wisconsin-Madison (RMRC Projects 46, 48, 53, and 61). In some cases, field modulus data were obtained via falling weight deflectometer (FWD) tests. Data from the BSRM test were compared to those from the LSME and FWD to account for the effects of the test conditions and scale on resilient modulus. Resilient moduli and plastic deformations obtained from the LSME were then used to develop a methodology for designing pavements with these materials. Two design methods using the AASHTO 1993 and AASHTO 2008 (Mechanistic Empirical Pavement Design Guide (MEPDG) were considered.

As mentioned earlier, modulus of a granular pavement layer depends not only the stress level but also the strain level thus layer thickness. An example of the SMR as a function of layer thickness is shown in Fig. 1. When considered for the typical range of base course thicknesses (i.e., 0.1 to 0.4 m), for the unstabilized base materials, the SRM is consistently higher for thicker base course layers due to the lower shear strain amplitude in thicker layers for the same surface load whereas it is essentially constant for the cementitiously stabilized materials. Two design approaches are provided for flexible pavements using unstabilized and stabilized recycled aggregates in the base: design using AASHTO-1993 design guide and lifetime expectancy-based design using the Mechanistic Empirical 9 Pavement Design Guide (MEPDG). To simulate field conditions, SRM from the LSME were used to develop the method.

Scaling

Resilient modulus is a non-linear function of stress conditions (i.e., bulk and octahedral stresses). The current models of resilient modulus takes this dependency on the state of stress in the base course but does not consider the effect of strain amplitude on resilient 8 modulus. In other words, a thicker base couse of the same granular material under the same wheel load would deform less even if the difference in stress level is taken into account because the thicker layer would have lower strains and consequently higher modulus. How this is taken into account is described in the next section on design.

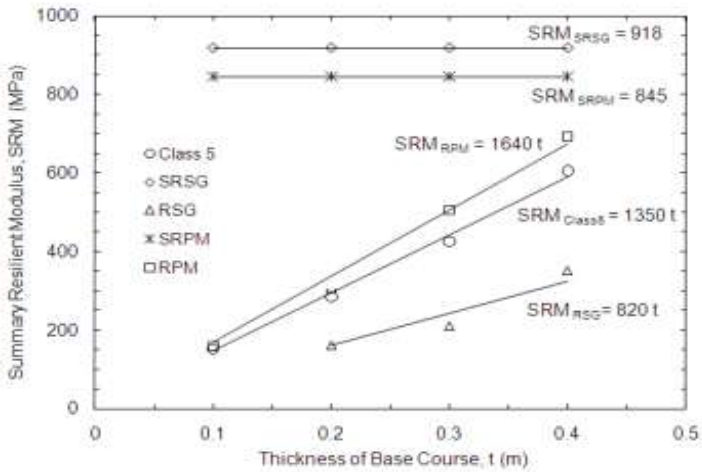

Figure 1: Summary resilient modulus (SRM) of Class 5 base, RPM, RSG, stabilized RPM and RSG (SRPM, and SRSG) as a function of base course thickness

Methods for Specification

When considering a recycled material for use as an unbound base course, the two most commonly used specifications are the gradation and the moisture-density relationship of the material. The gradation of a material can provide an indication of what the permeability, frost susceptibility, and shear strength of the material might be, and is determined through the use of material screening tests.[9] Screening tests are typically conducted through sieve analysis according to ASTM Standards C 117 and C 136, and AASHTO Standards T-27 and T-11. Some highway agencies and DOTs utilize their own screening test methods, such as Florida DOT FM1 T-027. Classification of soils is performed using the Unified Soil and AASHTO methods according to ASTM D 2487 and AASHTO M 145, respectively.

The determination of moisture-density relationships can help define the ideal density conditions that a material can achieve through compaction. Moisture-density relationships are established through compaction tests conducted according to the following standards: AASHTO T 99 Method C, AASHTO T-180 or ASTM D698, ASTM D 1557. Depending on the compaction effort to be used in the field, compaction tests can be performed in standard or modified variations. The information is used to determine 5the optimum moisture content (OMC) and the maximum dry density (MDD) of a material. Through testing of specimens prepared based on this data, material properties such as strength, stiffness and moisture susceptibility can be determined. Other aggregate classification methods involve the determination of the specific gravity, absorption and Atterberg limits of the soils. The specific gravity and absorption characteristics of a given recycled aggregate are determined using ASTM D 854, and Atterberg limits of recycled aggregates are assessed using ASTM D 4318, AASHTO T 89 and T 90.
If the data for this sample is removed, the resulting variances fall within the same variance. The sample Guthrie R1 was a composite taken at different locations with different equipment, and therefore the actual source for the erratic gradation of the material could not be determined. Gradation requirements for recycled materials vary from agency to agency. Unless indicated, the recycled materials referenced in this report passed the gradation requirements specified by the respective agencies. Blankenagel et al performed gradations on material taken from demolition sources as well as from relatively new materials sampled from batch-plant overruns and haul-back material sources. Batch plant overruns refer to excess concrete produced at a batch plant but never delivered to a job site, and haul-back material refers to excess concrete delivered to a job site but returned to the batch plant. The haul-back material was found to have more medium and fine materials than the demolition material. Although Blankenagel recognizes the source of the gradation differences could be due to crushing operations, the most likely reason is probably related to the mechanical breakdown tendencies of the materials. The haul-back material would have a higher porosity and lower strength due to being more properly consolidated and cured, resulting in a greater degree of pulverization regardless of crushing techniques. In the study conducted by Kuo, gradations of the RCA met Florida DOT specifications. However, for specifications regarding average gradation for each sieve, the standard deviations of the 3/4", 3/8", #4 and #10 sieves were all excessively high and each fell out of specification. The test would indicate that for recycled materials, these sieves might be considered more critical than the others.

Conclusion

Several important findings were noted in the course of this literature review. Kim et al compared the compaction properties of specimens prepared by typical proctor methods with specimens prepared with a gyratory compactor and found that the OMC and MDD of the specimens compacted via gyratory compactor were found to more closely correlate with field density measurements. Kim also found that at low confining pressures, pure aggregate and 50% blends of RAP and aggregate had an equivalent stiffness, but at high confining pressures the 50% blends had a higher stiffness than the pure aggregate. Bennert et. al found that pure specimens of RAP and 18RCA had higher resilient moduli than pure virgin aggregate specimens. Bennert also found that specimens of pure aggregate had higher shear strength than pure RAP or RCA specimens. This trend is supported in a study by Guthrie et al in which RAP/aggregate blends showed a decrease in shear strength as RAP content increased. In general, RPM seems to show a better response than natural aggregate for similar gradation and compaction in tests that induce relatively smaller strains such as resilient modulus tests than tests that induce large strains such as triaxial compression or CBR tests.

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